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TITLE: DETERMINATION OF PROTECTION FACTORS FOR TANDEM HEPA FILTERS

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DETERMINATION OF PROTECTION FACTORS FOR TANDEM HEPA FILTERS

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High efficiency filters are frequently installed in series to provide large reductions in the number of particles in the airstream. However, there is little information on filter performance with respect to size characteristics of the airborne particles. This information is frequently required when filters are used for contamination control involving specific materials. Contamination control requirements are varied and may be related to particle number, or the mass or number of particles in a specific size range. The efficient design of a satisfactory system requires information on performance with respect to aerosol characteristics.

Filtration theory is not sufficiently developed to predict the performance of high efficiency filters. Theory is sufficiently developed to indicate performance trends. Thus, theory may be combined with performance data to provide insight into the probable performance with respect to aerosol characteristics.

The theoretical model used to investigate the performance of high efficiency particulate air (HEPA) filters is described by Davies[1] in a comprehensive review of filtration work up to 1973. The aerosol characteristics that are related to filter performance are particle size and particle density. This model incorporates both of these parameters and covers the size range of maximum penetration.

Filtration is a complex process involving a number of mechanisms. On a theoretical basis the mechanisms are treated individually, or at best two mechanism are considered simultaneously. There is some justification for considering the mechanism independently as one mechanism frequently predominates for a given particle size or set of filter operating conditions. However, this procedure is probably not valid in the range of minimum efficiency as several collection mechanisms are of comparable importance in this size range. The particle size range of minimum efficiency is also of principle interest in characterizing the performance of air cleaning systems as it defines the minimum in performance. Davies recommends the summation of four mechanisms to determine overall filtration efficiency. Three of the mechanisms are independent: diffusion, interception, and inertial impaction. The fourth mechanism considers the increased collection due to interaction of diffusion and interception. The efficiency expressions for each mechanism were developed by Stechkina, Kirsch, and Fuchs[2,3,4] with some modifications recommended by Davies.[1]

Several assumptions were necessary in the development of the model and in application of the model to HEPA filters. These assumptions will contribute errors in the prediction of efficiency magnitude. However, the assumptions should have minimal effect on determining the relationships between the important parameters or on the characteristics of efficiency curves.

The theoretical model uses the flow field described by Kuwabara for parallel cylinders.[1] Figure 1 is a scanning electron micrograph of a HEPA filter mat indicating the random arrangement of the fibers. However, a large fraction of the flow may be similar to the model as over most of the fiber length the near neighboring fibers are approximately parallel.

Application of the model requires the use of some representative fiber diameter to relate individual fiber efficiency to the performance of a fiber mat. The fiber diameter used for this model is the arithmetic average diameter determined by measuring the fibers from scanning electron microscope photomicrographs. The length of fiber in unit volume of filter was then determined using the average fiber diameter and the porosity of the filter mat. The porosity of the filter mat was determined by weighing pieces cut from a filter, measuring the pieces to determine volume and calculating porosity, assuming a bulk density of 2.6. It is difficult to estimate the result of using this average diameter on the prediction of overall filter efficiency. Filtration theory indicates that smaller fibers are more efficient collectors. Possibly some weight should be applied to this fact rather than use of the average diameter when the representative fiber diameter is defined. At this time there is little information available on what type of weighting should be used to select a representative diameter.

The parameters used with the model to calculate filtration efficiency are listed in Table I. The normal ambient variations in temperature, pressure, and viscosity would not alter the results significantly. The approach velocity, defined as the total flow divided by filtration area, was selected because it is the velocity encountered when HEPA

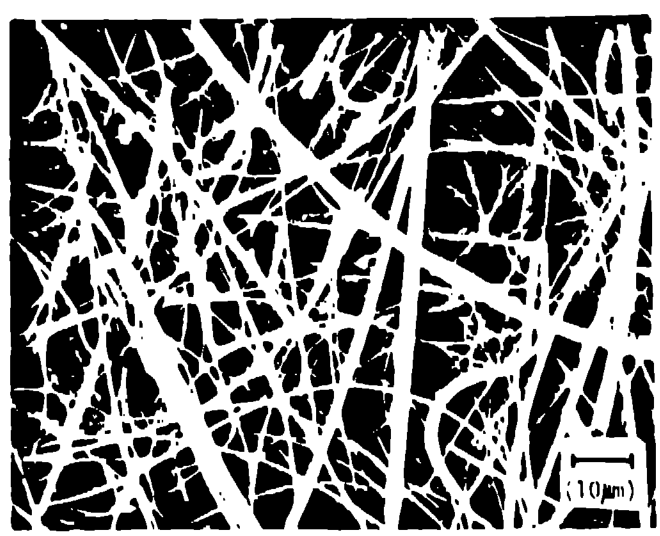

Figure 1. Scanning electron microscope photograph of HEPA filter media.

TABLE I

PARAMETERS USED TO CALCULATE HEPA FILTER EFFICIENCY

Filter fiber diameter	0.49 microns
Filter porosity	0.038
Filter thickness	0.089 cm
Approach velocity	5.0 cm/s
Viscosity	181.5 micropoises
Temperature	22°C
Barometric pressure	760 mm Hg

filters are operating at flow capacity. HEPA filters are frequently operated at flow rates below capacity, which would result in some differences in collection efficiency.

The results of the calculations made with this model are shown in Figure 2 for aerosol particles of four densities. The penetrations shown in Figure 2 are considerably higher than are normally measured with HEPA filters. However, the shape of the curves are similar to experimental penetration curves[5] and the decrease in penetration with increasing particle density is also consistent with experimental results.[6] The particle size of minimum efficiency and the percent penetration values are listed in Table II.

The high collection efficiency of HEPA filters had resulted in limited data on collection efficiency as a function of particle size. The recent availability of single particle aerosol spectrometers provides an instrument that can size particles from the low concentrations encountered downstream of HEPA filters. The size range covered by the spectrometer has also provided information in the range of minimum efficiency.[7] This data is shown in Figure 3 in terms of the protection factor or the inverse of the fractional penetration. The solid line in Figure 3 is given by a second order regression fit to the data points. These points are for one filter challenged by a dioctyl phthalate (DOP) aerosol. The regression curve indicates that for unit density particles and normal filter operation conditions, the size of maximum penetration for this filter was 0.21 μm.

The regression curve may be utilized to normalize the theoretical curves shown in Figure 2. Figure 4 shows the theoretical curves normalized to the same peak efficiency (Table II) as the regression curve for unit density particles. The shape of the theoretical curves and regression curve are somewhat different. This is probably the result of using a second order regression fit to the data and because the data covered a narrow particle size range (0.075 to 0.3 μm). However, for investigating the characteristics of performance by successive stages of HEPA filters, this difference is not significant. The normalized theoretical efficiency curves may now be used to estimate the performance of multiple stages of HEPA filters against a variety of aerosols.

Table III gives the penetration results for four different aerosols. These results were determined by (1) dividing the aerosol into ~30 size intervals, (2) determining the mass and number

Figure 2. Theoretical filtration efficiency of HEPA filters.

TABLE II

PARTICLE SIZE OF MAXIMUM PENETRATION AND PERCENT PENETRATION

Particle Density (g/cm)	Particle Size of Maximum Penetration (Microns)	Percent Penetration	
		Davies Model	Normalized
0.50	0.16	4.69	8.46E-3
1.00	0.15	4.36	7.87E-3
3.00	0.14	3.46	6.26E-3
7.00	0.12	2.47	4.46E-3
9.00	0.12	2.17	3.92E-3
11.00	0.11	1.91	3.45E-3

Figure 3. Experimental protection factors for HEPA filter challenged with unit density liquid aerosol particles.

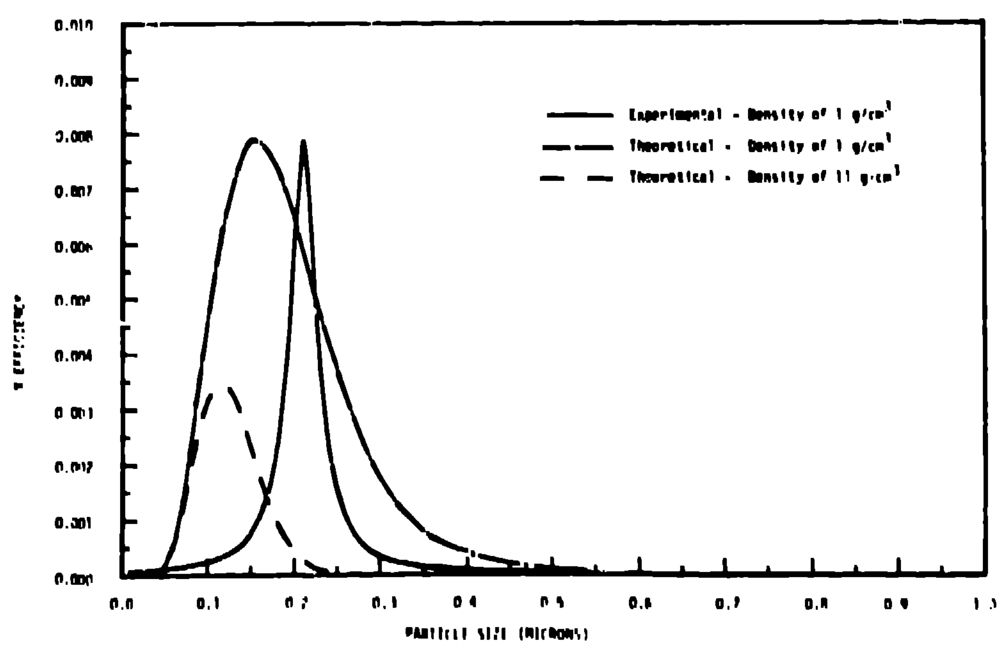

Figure 4. Experimental filtration efficiency curve and normalized theoretical efficiency curves.

TABLE III

AEROSOL PENETRATION THROUGH TWO STAGES OF HEPA FILTERS

Challenge Aerosol Parameters			Stage One Penetration		Stage Two Penetration	
Cmd[a]	σ_g[b]	ρ[c]	Number %	Mass %	Number %	Mass %
1.0	2.0	1.0	0.000287	<0.00000013	0.00388	<0.0000008
0.5	2.0	1.0	0.001260	0.00002050	0.00501	0.0026100
1.0	2.0	11.0	0.000019	<0.00000013	0.00204	<0.0000008
0.5	2.0	11.0	0.000160	0.00000039	0.00216	0.0000074

[a]Count median diameter (microns).
[b]Geometric standard deviation.
[c]Density (grams per cubic cm).

fraction in the interval, (3) determining the average filtration efficiency over the interval using the curves from Figure 4, (4) determining the number and mass fraction penetrating in each interval, and (5) summing over the intervals to determine efficiency. The number and mass efficiencies in Table III illustrate the wide variation in penetration between stage one and stage two. The aerosol penetrating the first stage is enriched in the particle sizes for which the collection efficiency is lowest. Thus, with respect to number, the efficiency varied from four times lower to an order of magnitude lower. The variation with respect to mass penetration is greater although the mass penetration is significantly lower than number penetration. The variation is more apparent when expressed in terms of the protection factor. The protection factors determined from the same data are listed in Table IV. The protection factor will always be greater than the value measured at the size of minimum efficiency. The stage two protection factor is approaching this minimum value. The measured protection factor is for unit density particles and would not be as large for less dense particles.

The results shown in Tables III and IV are based on the protection factor measurements of only one HEPA filter. The actual value of these numbers should not be generalized to predict performance. The numbers do illustrate the effect of using successive stages of filtration and the errors that may results when comparing different types of efficiency data, i.e., mass efficiency to number efficiency. A reliable design of contamination control with HEPA filters requires that the material to be controlled be well characterized with respect to particle size distribution and density. Filter performance data that is pertinent to the desired control should also be used. If the desired control is with respect to particle number as with some viable aerosols, then number data should be used. The same is also true when containment control is related to material mass.

The above considerations relate only to the performance of the filtration media. In practical applications, the entire system including filter mounting systems, leaks, and airflow characteristics must also be considered.

The single particle aerosol spectrometer used to carry out the protection factor measurements is essentially a zero background counting device and can be used to measure the efficiency of two stages of filters with respect to particle number and size. Measurements carried out on two stages of HEPA filters generally support the drop in efficiency noted between stage one and two in this study.[5,7]

ACKNOWLEDGMENT

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TABLE IV

PROTECTION FACTORS PROVIDED BY TANDEM HEPA FILTERS

Challenge Aerosol			Protection Factors					
			Stage One		Stage Two		Combination	
CMD[a]	σ_g[b]	ρ[c]	Number	Mass	Number	Mass	Number	Mass
1.0	2.0	1.0	3.48E5	>7.69E8	2.58E4	>1.25E8	8.98E9	>9.6E12
0.5	2.0	1.0	7.94E4	4.88E6	2.00E4	3.83E4	1.59E9	1.87E11
1.0	2.0	11.0	5.26E6	>7.69E8	4.90E4	>1.25E8	2.58E11	>9.6E12
0.5	2.0	11.0	6.21E5	2.56E6	4.63E4	6.99E7	2.87E10	1.8E12

[a]Count median diameter (microns).
[b]Geometric standard deviation.
[c]Density (grams per cubic cm).